BELLCOMM, INC.

SUBJECT: Apollo Free Return Reentry Point Analysis Case 310

DATE: Revised June 20, 1966

FROM: S. F. Caldwell
V. S. Mummert

ABSTRACT

This memorandum examines the location of the free return reentry points for the nominal free return profile and several possible variations. There are a number of operational problems which can serve to constrain the reentry point. The Command Module is designed to land on water, and so land landings are undesirable. Also landings in unfriendly territory or far from the recovery forces are undesirable.

Because of the flexibility which is built into the nominal Apollo Mission the free return touchdown points from a single launch window may vary over 120° longitudinally and over 40° latitudinally. This wide variation almost always results in some possible trajectories from a given launch window having undesirable free return touchdown points. The situation may be partially remedied by reducing the flexibility. Another approach is to perform a maneuver on the free return transearth leg which places touchdown at an acceptable point. It is shown that such a maneuver by the Service Module or the LEM descent propulsion system will guarantee a touchdown in a satisfactory geographic region for a ΔV cost of less than 700 fps. Also, a study of the so-called "free return squared" trajectory indicates that water landings can be assured for this profile with a maximum ΔV penalty of about 300 fps.

(NASA-CR-78347) APOLLO FREE RETURN POINT ANALYSIS (Bellcomm, Inc.) 25 p

N79-71986

[redacted]

Unclas
00/13 12903

FACILITY FORM

25 (ACCESSION NUMBER)

(THRU) 2C

(PAGES)

(CODE) 30

Cr-78347 (NASA CR OR TMX OR AD NUMBER)

(CATEGORY)

[redacted]

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MEMORANDUM FOR FILE

INTRODUCTION

Under current plans, Apollo will fly a free return trajectory after translunar injection. If the translunar injection cutoff conditions are perfect, the spacecraft could circumnavigate the moon and return to earth with the proper reentry angle. The free return trajectory is principally a crew safety device in case of spacecraft failures. Under nominal conditions, the transearth leg of the free return trajectory will not be traversed. It is only in the event of some contingency that the transearth leg and its associated reentry and touchdown points become important.

Heretofore, free return trajectory analysis has assumed that the earth reentry point of the free return leg was unconstrained. The only restrictions which have been placed on the trajectory shaping are that the reentry be posigrade at the proper flight path angle and that the altitude of perilune be between 40 NM and 80 NM.

There are a number of operational problems which might serve to constrain the reentry point. The Command Module is designed to land on water; land landings are undesirable. Also, landings on unfriendly territory or far from the recovery forces are undesirable.

This memorandum shows how the geographic free return reentry point changes with launch date, with launch window, and with the trajectory parameters within a launch window (launch azimuth, altitude of perilune, etc.). The touchdown points are then related to the reentry points via the permissible reentry range. While quantitative results are given only for earth launches in February 1968, general rules are presented which relate the free return reentry point to the translunar injection point.

THE BEHAVIOR OF FREE-RETURN TRAJECTORIES

A brief review of the behavior of free return trajectories will be useful for the analysis which follows. Figure 1 sketches a typical trajectory in earth-moon space. For simplicity the entire trajectory is assumed to lie in a single plane. The position of the free return reentry point can be related to the translunar injection point by the total flight time and the following angles.

Φ_1 = translunar transfer angle $\cong$ 170°

X = angle between entry point and exit point of the moon's sphere of influence (see figure 1) $\cong$ 5°

Φ_2 = transearth transfer angle $\cong$ 157°

Then the angle from injection to reentry is $\theta = \Phi_1 + X + \Phi_2$ where positive angles are measured eastward. Since θ is nearly 360°, it can be more simply expressed as

$$\theta = \Phi_1 + X + \Phi_2 - 360° \cong -30°$$

Thus the inertial injection point and the inertial reentry point are separated by about 30 degrees. It is clear that if the earth turns through an integral number of revolutions from injection to reentry, the earth fixed injection and reentry points will also be separated by about 30 degrees.

The above analysis assumed that the entire trajectory lays in a single plane, the earth-moon plane. As the transearth leg is rotated out of this plane, by varying the equatorial inclination of the earth centered ellipse, the reentry point traces out on the surface of the earth a circular locus with a radius of about 20 degrees. Since Apollo free return reentries are constrained to be posigrade (reentry azimuth between 0° and 180°), only the left half of this circular locus need be considered (see schematic on Figure 2).

It should be noted that the total variations in latitude on figure 2 is about 40° while the longitude variation is about 20°.

The next obvious step is to draw in the loci of touchdown points corresponding to the reentry points of Figure 2. Figure 3 sketches such loci for reentry ranges of 1500 NM (25° of central arc) and 2500 NM (42° of central arc). The shaded area on Figure 3 is the total potential touchdown area for the reentry locus shown. The reader will note that if the reentry range were 1200 NM, all the trajectories would touchdown at a single point, point A on Figure 3. Point A also acts as a focus for the other loci and can serve as an indicator for them. When point A is specified the other loci can be reconstructed.

Figure 4 shows an actual set of loci; they are of course not perfect semi-circles as in Figure 3 but the correspondence with theory is good and they do tend to focus around a point. It must be emphasized that the set of loci illustrated on Figure 3 is only one member of a family of sets for the Pacific injection window on February 1, 1968. The remainder of the memorandum will be concerned with the position of the focal point (the indicator for a set of reentry and touchdown loci) as a function of launch date and of various trajectory parameters.

FACTORS WHICH AFFECT POSITION OF FOCAL POINT

A prior section has shown that the reentry loci and thus the focal point can be related to the translunar injection point if the total time of flight is known. Hence, the factors which affect the position of the focal point can be broken into two groups: those which affect the total trip time and those which affect the geographic position of the injection point.

FACTORS WHICH AFFECT TOTAL TRIP TIME

The total trip time varies with

1. Date of Launch
2. Altitude of perilune
3. Free return equatorial inclination
4. Launch Window (Atlantic or Pacific Injection)

Of these four factors, date of launch greatly predominates. The total trip time varies by about 16 hours over a lunar month. Altitude of perilune and free return inclination are optimization parameters which are used to minimize the spacecraft fuel required to reach a given lunar landing site. By the trajectory ground rules, perilune altitude can be freely varied from 40 NM to 80 NM. As has been pointed out, free return inclination can be freely varied over all posigrade values. Trip time changes by about one hour over the total allowable range of perilune altitudes with the shortest flight times occurring at the lowest perilune altitudes. Trip time varies by about one hour over the total allowable range of return inclinations. This latter fact accounts for the slight ellipticity of the loci on figure 4. The difference in trip time between the two daily launch windows varies from zero to one hour and can be accounted for as due to the differing inclination of the translunar trajectory to the earth-moon plane and to the differences in launch times.

Figure 5 shows total free return trip time as a function of date and time of launch over the calendar month of February, 1968. Trip time on Figure 5 is shown as a band; this band encompasses trip times for both daily launch windows, all posigrade free returns, and all perilune altitudes between 40 NM and 80 NM. From this figure it is easily seen that date and time of launch are the dominating factors in trip time deviation.

As has been pointed out, if the earth turns through an integral number of revolutions from translunar injection to reentry, these two points will be separated geographically by about 30°. Fractional revolutions of the earth will result in a longitudinal displacement of the geographic reentry point. In other words, the geographic position of the focal point undergoes a purely longitudinal displacement with variation in flight time. From Figure 5 it can be seen that for any particular launch window, total trip time can vary by about 2 hours. Thus, the longitude of the reentry focal point can vary by 30° due to variations in trip time. (The earth rotates at 15° per hour.)

FACTORS WHICH AFFECT THE GEOGRAPHIC POSITION OF THE INJECTION POINT

The position of the injection point varies with

1. Launch Window (Atlantic or Pacific Injection)

2. Date of Launch

3. Launch Azimuth

4. Number of Earth Parking Orbits.

The two daily launch windows result in trajectories whose translunar injection points may occur on opposite sides of the earth. The injection points for one launch window (type P) fall in the general area of the Pacific Ocean and those for the other window (type A) fall over the Atlantic and Indian Oceans. When the moon is near its maximum or minimum declination, the two sets of injection points will be close together; when the moon is near the equator the injection points will be nearly 180° apart. Thus the choice of launch window greatly affects the position of the injection point.

The injection points for each daily launch window move with the launch date. Here the movement is about 13° per day - the angular rate of the moon.

A variable launch azimuth is used to provide a launch window and as would be expected the required position of the injection point moves by 15° per hour, the rotational rate of the earth, during the launch window. Thus during a four and one-half hour launch window, (the window available for a variation of launch azimuth from 72° to 108°) the injection point would move longitudinally through 68°. The latitudinal variation during a launch window is small.

Under current mission ground rules, translunar injection may take place during either the second or the third earth parking orbit. These two injection opportunities are separated in time by about 90 minutes and so the geographic injection positions are separated in longitude by about 22°.

By adding the variation in the geographic position of the injection point due to the desire for a launch window and the variation which results from having two injection opportunities, it can be seen that the injection position may vary longitudinally by 90° over one launch window. Of course, longitudinal displacement of the injection point results in an identical displacement of the reentry focal point.

Figures 6a and 6b show the movement of reentry focal points as a function of launch date and launch window during February 1968. For each date and window, one point is shown. It represents a 90° launch azimuth, translunar injection on the second orbit, and an 80 NM perilune altitude.

On February 3, 10, 17 and 24 a horizontal line is shown to illustrate the variation of the focal point with launch azimuth and with injection opportunity. Points are set out on the lines to denominate the following cases:

1. Launch azimuth of 72°/Injection on second earth orbit (extreme east on each line)

2. Launch azimuth of 90°/Injection on second earth orbit

3. Launch azimuth of 108°/Injection on second earth orbit

4. Launch azimuth of 108°/Injection on third earth orbit (extreme west on each line)

The distinct differences in shape between the loci of focal points on Figures 6a and 6b can be explained by the nature of the two elements which determine the position of a reentry focal point: the translunar injection point and the total trip time. On February 7 both the Atlantic and Pacific injections are near Australia and both reentry focal points are in the South Indian Ocean. On succeeding days the Atlantic injection point moves <u>northwest</u> until on February 20 it is near Florida. This movement would tend to draw the reentry focal point in a northwesterly direction also. However, over this two week time period, the total flight time has first decreased sharply tending to draw the focal point east and then increased slightly. Since the time of flight factor dominates, the focal point moves northeast from February 7 to February 13 and is then drawn northwest. During much of this period the relationship between the movement of the injection point and the change of flight time was one of interference so there was a relatively small movement of the focal point. Between February 7 and February 20, the Pacific injection point moves <u>northeast</u> from Australia until it too is near Florida. However, its movement reinforces the changing total trip time so that the reentry focal point for Pacific injections moves over a relatively large area. On February 20, the reentry focal points from the Atlantic and Pacific injections are close together again in the eastern Mediterranean but the Atlantic has come from the East and the Pacific from the west.

TOTAL DISPLACEMENT OF A FOCAL POINT

A longitudinal displacement of the focal point of 30° was previously shown because of variations in trip time. When this is added to the variations due to the location of the injection point, it can be seen that each point on the loci of Figures 6a and 6b has a total possible deviation of 120°. This deviation or uncertainty in the geographic position of the reentry focal point is due to the desire for a launch window, for two injection opportunities, and for a variable perilune and return inclination. Thus, the factors which give the mission operational and performance flexibility are the ones which cause the free return reentry point to move over a wide geographic area.

In one respect a wide variation in the reentry point for a single day is fortunate: almost every launch window will have some free return trajectories which result in acceptable reentry points. If all of the trajectories from a given launch window fell in a small area which was over land, a whole launch window could be eliminated by a ground rule which required a water landing. On the other hand a wide dispersion in reentry points is unfortunate: almost every launch window has some trajectories which result in undesirable reentry points.

Of course the range control built into the reentry guidance system can be used to vary the touchdown point over a 17° central angle. However in a great many cases this control is insufficient.

ONE REMEDY: REDUCE FLEXIBILITY

One obvious solution to the problem of undesirable reentry and landing points is to reduce mission flexibility. Since the possible reentry points from a given launch window fall over such a wide area, the mission analysis could be restricted to that subset of free return trajectories which result in acceptable reentry points.

The mission flexibility can be divided into two subsets: performance flexibility and operational flexibility. The range of the two performance parameters, altitude of perilune and free return inclination, might be restricted so as to place the free return touchdown point over water. However, it has been seen that these parameters exert a relatively small influence on the position of the touchdown point, and to so restrict their range can result in increased SM fuel requirements on the order of a thousand pounds.

It is also possible to restrict the range of the operational parameters, launch azimuth and translunar injection opportunity. On Figure 6 it can be seen that these two parameters result in a 90° longitudinal variation in the free return reentry and touchdown points. If the Program were content to go with a one hour launch window and one injection opportunity, the free return focal point could be restricted to any preselected 15° segment of the total 90° variation.

Also from Figures 6a and 6b it is apparent that the choice of the launch window (type of injection) and of the date of launch are strong factors. Which of the two daily launch windows is to be used is determined by a variety of performance and operational considerations. It could conceivably be chosen so as to place the free return touchdown point over water. These figures also show that certain launch windows will have all their free return touchdown points over water with no sacrifice in flexibility. In other words, a water landing can be had by sacrificing mission opportunities.

ANOTHER REMEDY: PROPULSIVE CORRECTIONS

A solution which may be preferable to a reduction in flexibility is to perform a propulsive maneuver on the free return leg so as to change the total trip time. For every hour the trip time is changed, the geographic longitude of the reentry point will be changed by about 15°. Figure 7 shows that ΔV cost varies by roughly 100 fps per hour change in flight time if the ΔV correction is made at the moon's sphere of influence on the transearth leg of the free return trajectory. If the correction were applied earlier in time, even greater efficiency would result. Even if such a propulsive maneuver is planned, there is still justification for retaining the circumlunar free return trajectory. Free return trajectories can be thought of as a special subset of all earth-moon trajectories. This special subset of trajectories, if perfectly executed, requires no propulsive maneuvers to return to the earth. Hence an heuristic argument can be advanced for the proposition that members of this special subset will require the least propulsive maneuvering to reach a water landing point on the earth.

Also shown in Figure 7 is a typical plot of reentry velocity as a function of the change in flight time. Of course, the reentry velocity of the uncorrected free return trajectory varies from day to day and with the choice of optimization parameters; the total possible change is about 80 fps. The Apollo CM is constrained to reenter at velocities less than 36,500 fps.* Figure 7 indicates that even with changes in trip time of 8 hours this constraint will not be violated. If 700 fps were available to vary trip time, figure 7 indicates that a potential change of about $\pm$ 6 hours would be possible. At 15° per hour, a reentry longitude flexibility of more than 180° would result. With this kind of flexibility a water landing could be guaranteed. As presently configured, the LEM descent propulsion system can deliver 1900 fps to the fully loaded spacecraft. Of course the SPS, in working condition, can easily perform this maneuver. The foregoing facts indicate that an operationally acceptable free return reentry and landing can be accomplished by the use of a DPS or SPS maneuver on the return leg.

Another scheme involving a propulsive maneuver is the so-called "free return squared" trajectory. Under this strategy, translunar injection is targeted such that a water landing is guaranteed. This is most simply accomplished by raising the altitude of perilune so as to increase the total free return trip time.

At some point soon after translunar injection, the SPS would then be used to correct the trajectory to one having an optimum perilune altitude. After the correction the free return characteristic would be retained but the free return landing point would be unconstrained. The ΔV penalty and the required change in perilune altitude are shown on Figure 8 as a function of the required change in total free return trip time. This figure indicates that only about 300 fps is required to accommodate a time change of 12 hours if the correction is made 10 hours after translunar injection. Figure 9 indicates that 10 hours after translunar injection is a nearly optimum point to make the corrective maneuver. This "free return squared" strategy has one important advantage over a correction on the return leg--a free return water landing will be guaranteed until the SPS has been fired for the first time. The most important disadvantage is, of course, that a propulsive correction will exist in the nominal translunar trajectory; fuel must be provided for this correction out of the nominal ΔV budget.

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*Apollo Program Specification, §3.5.1.22, May, 1965.

SUMMARY

Because of the flexibility which is built into the Apollo Mission, the free return reentry focal points from a single launch window vary longitudinally over 120°. This wide variation almost always results in some trajectories having operationally undesirable free return touchdown points. The situation may be partially remedied by reducing the flexibility. Another approach is to perform a maneuver on the free return transearth leg which places touchdown at an acceptable point. It is shown that a DPS or SPS maneuver of less than 700 fps will guarantee a touchdown in a satisfactory geographic region. A study of the so-called "free return squared" trajectory shows that a water landing can be assured by this scheme with a maximum ΔV penalty of about 300 fps.

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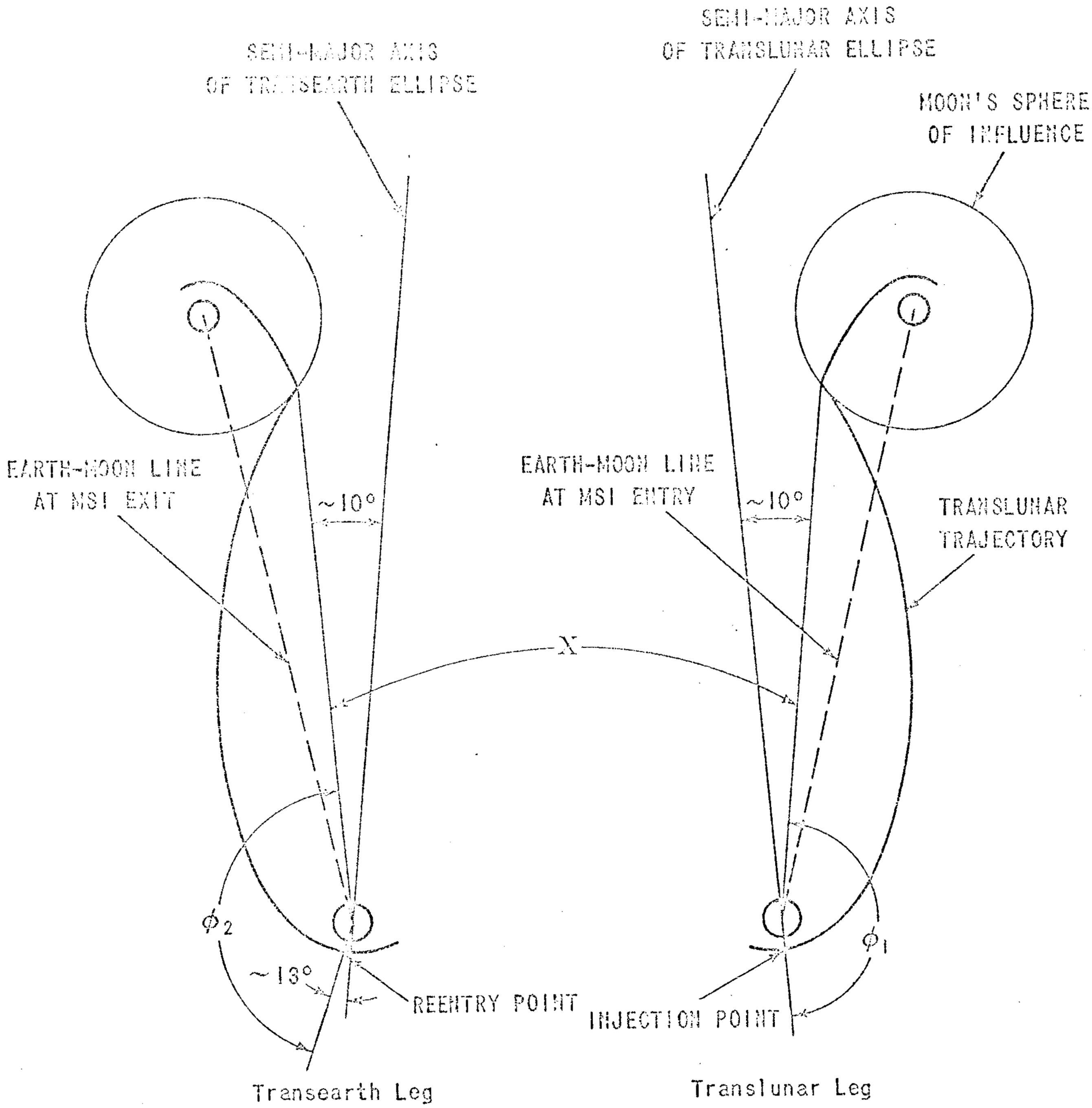

FIGURE 1 GEOMETRY OF A FREE RETURN TRAJECTORY IN EARTH-MOON SPACE
(PATCHED CONIC SCHEMATIC)

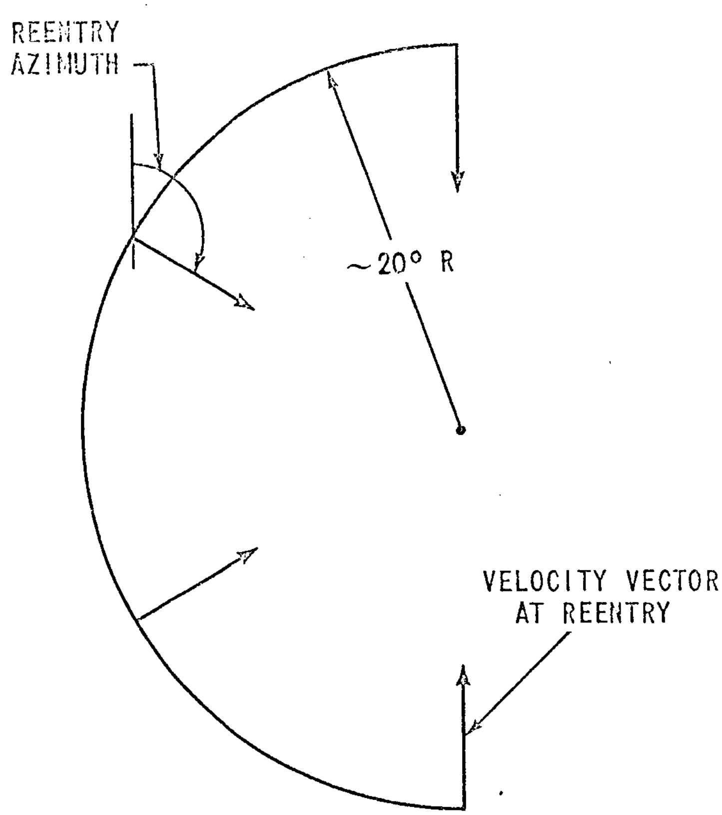

FIGURE 2: LOCUS OF REENTRY POINTS ON THE EARTH'S SURFACE

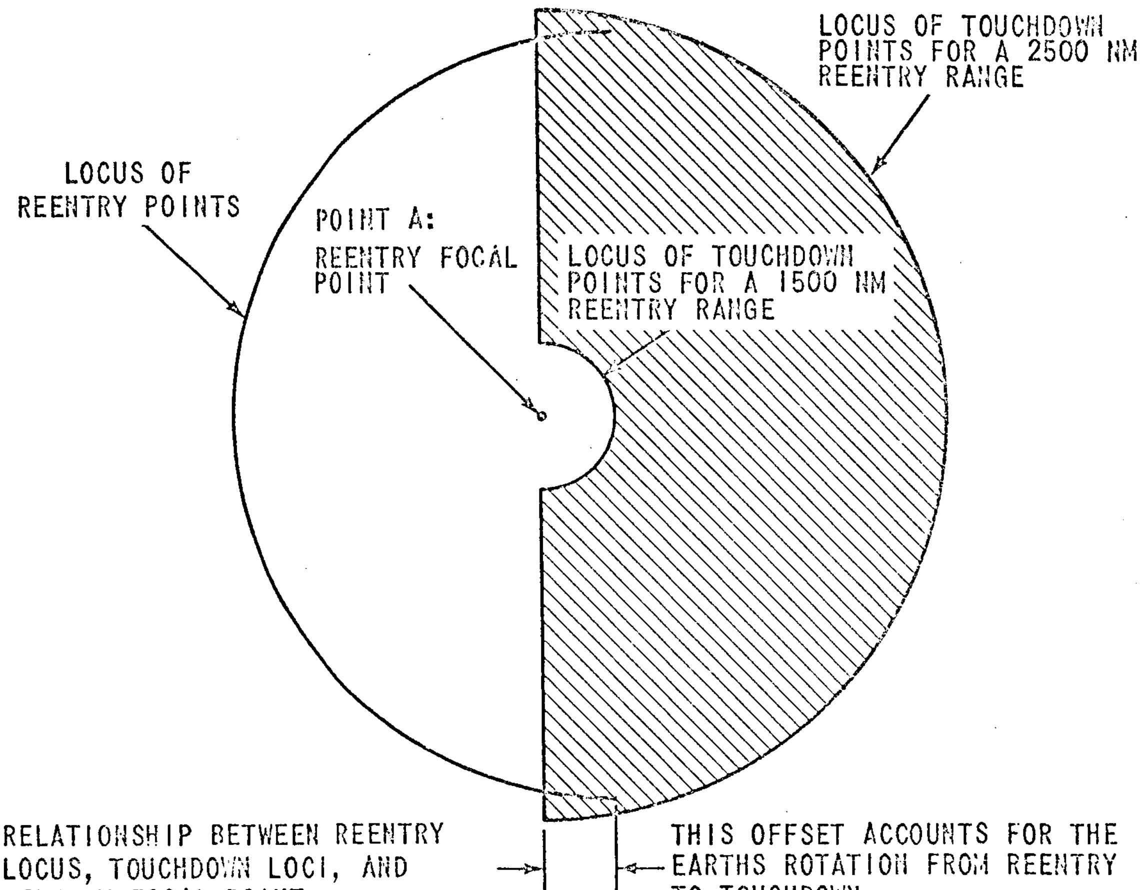

FIGURE 3: RELATIONSHIP BETWEEN REENTRY LOCUS, TOUCHDOWN LOCI, AND REENTRY FOCAL POINT

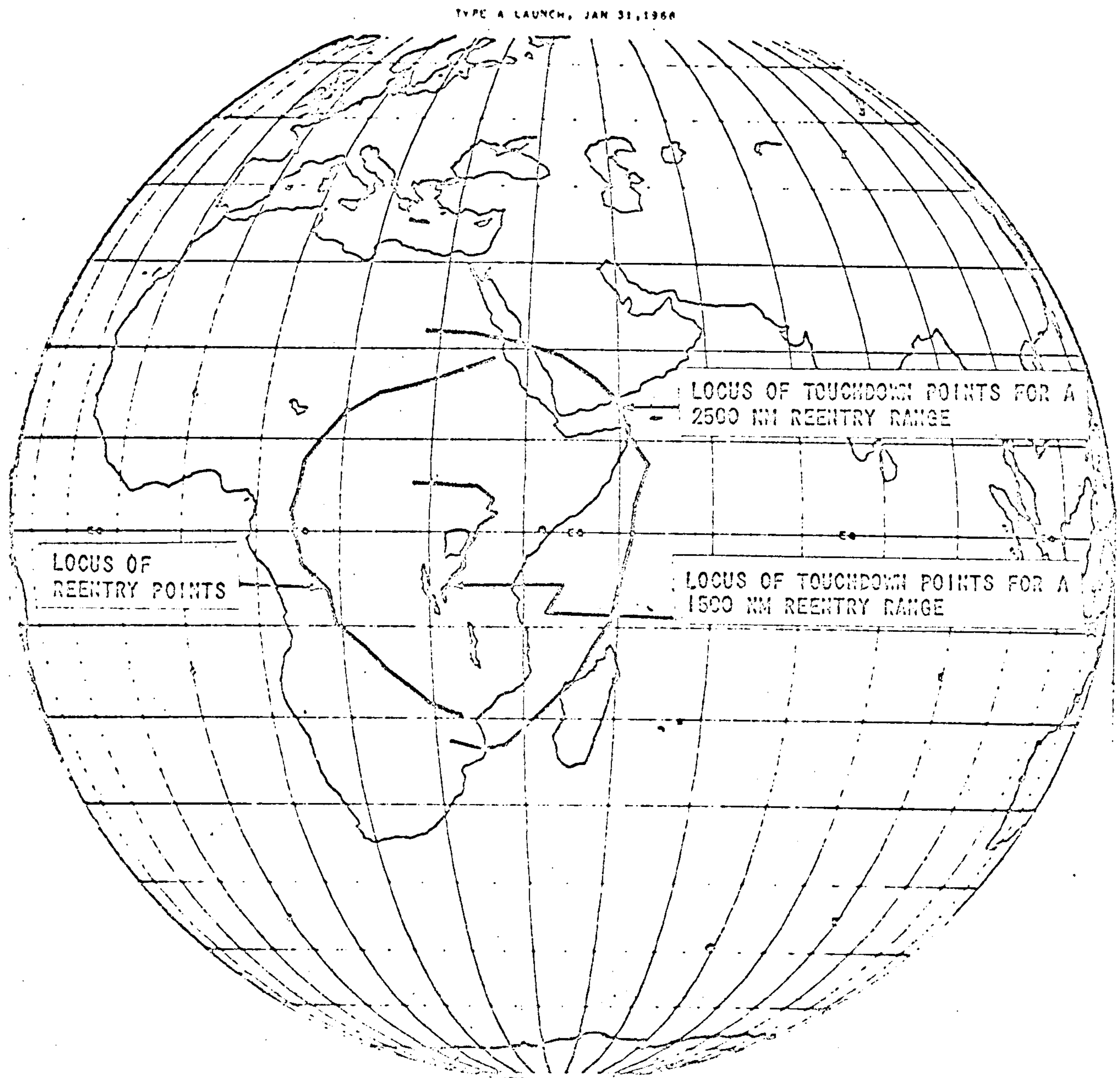

FIGURE 4 THE FREE RETURN REENTRY AND TOUCHDOWN LOCI FOR PACIFIC INJECTIONS ON FEBRUARY 1, 1968

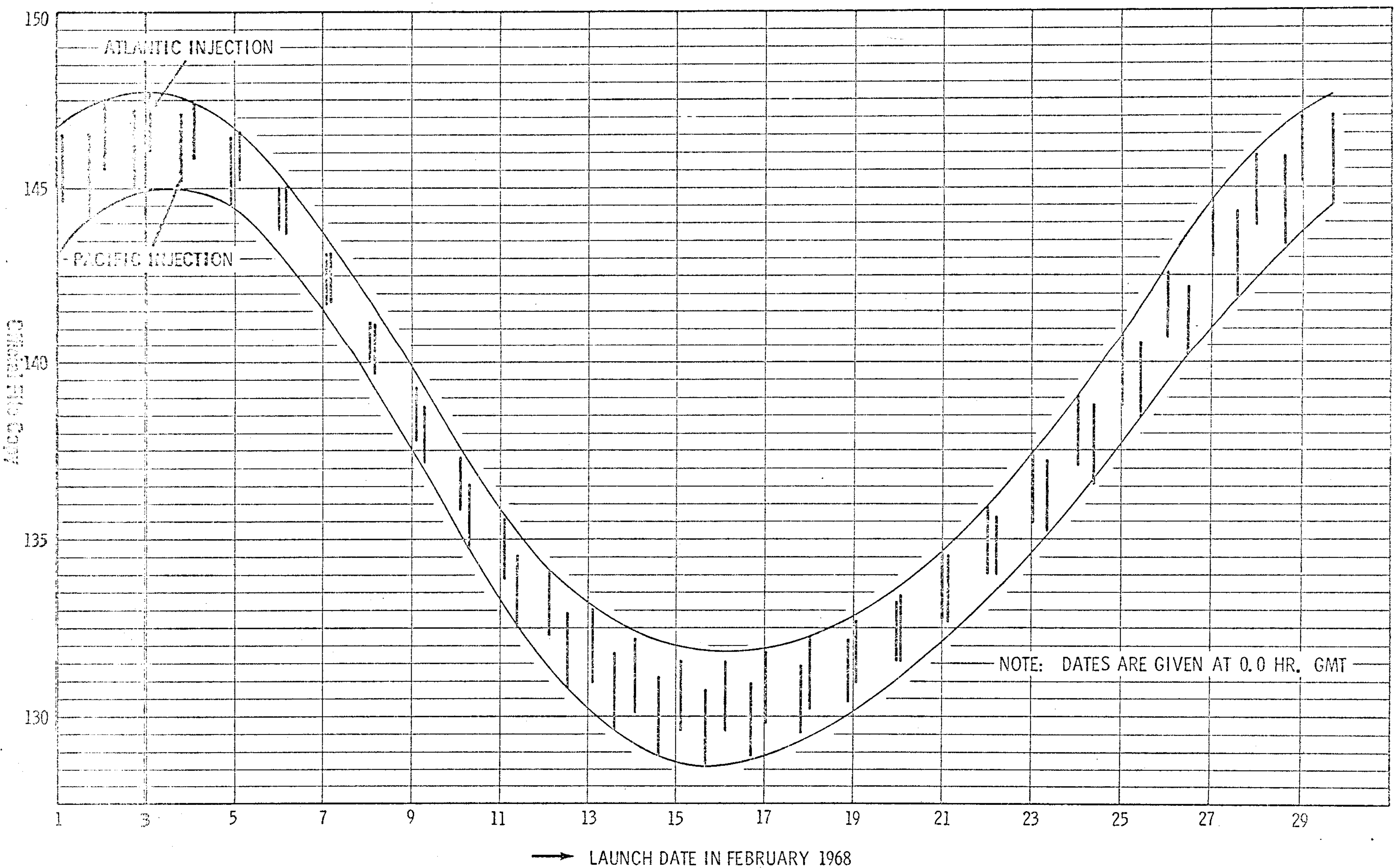

FIGURE 5 TOTAL TRIP TIME AS A FUNCTION OF LAUNCH DATE IN FEBRUARY 1968

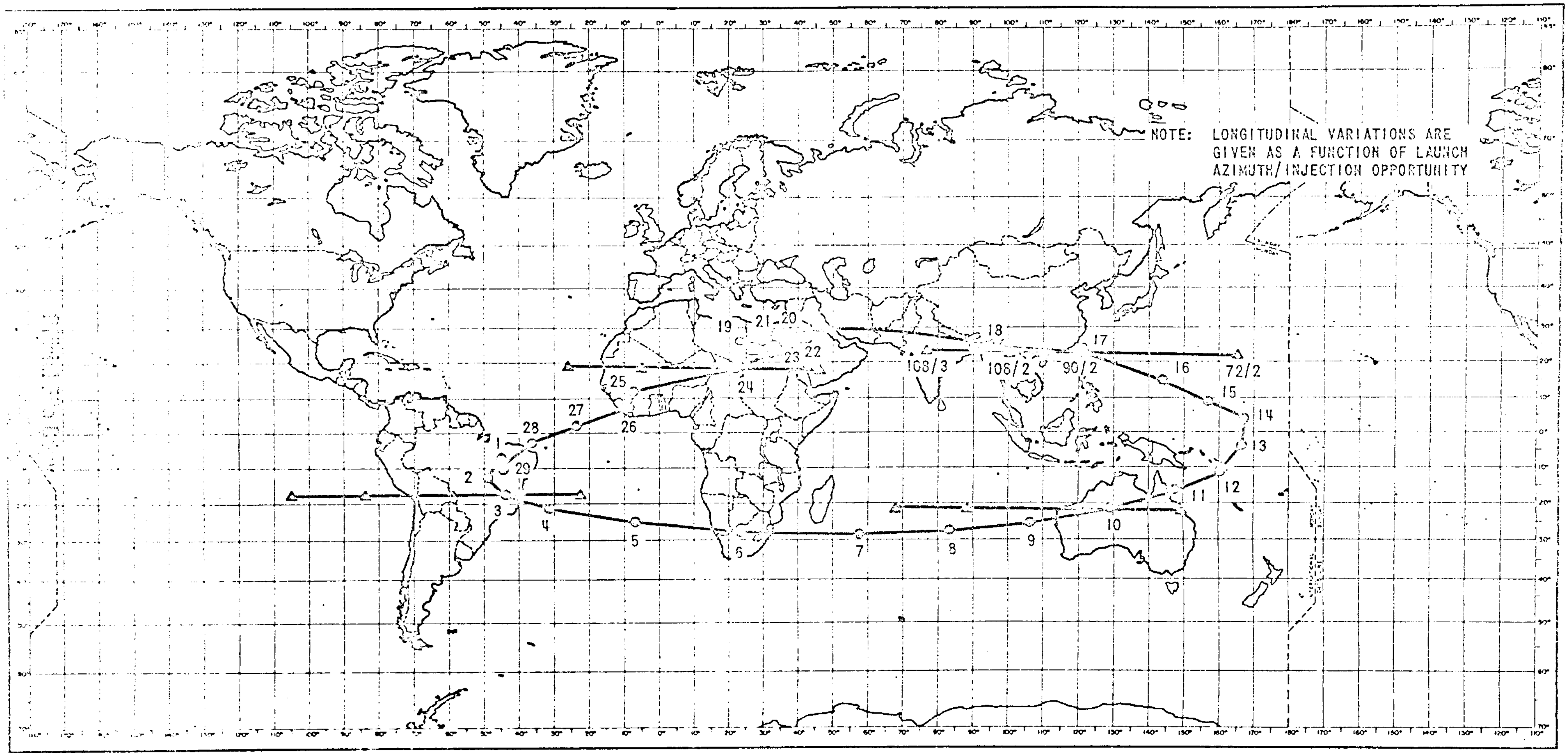

FIGURE 6A: ATLANTIC INJECTIONS

FREE RETURN FOCAL POINTS DURING FEBRUARY 1968

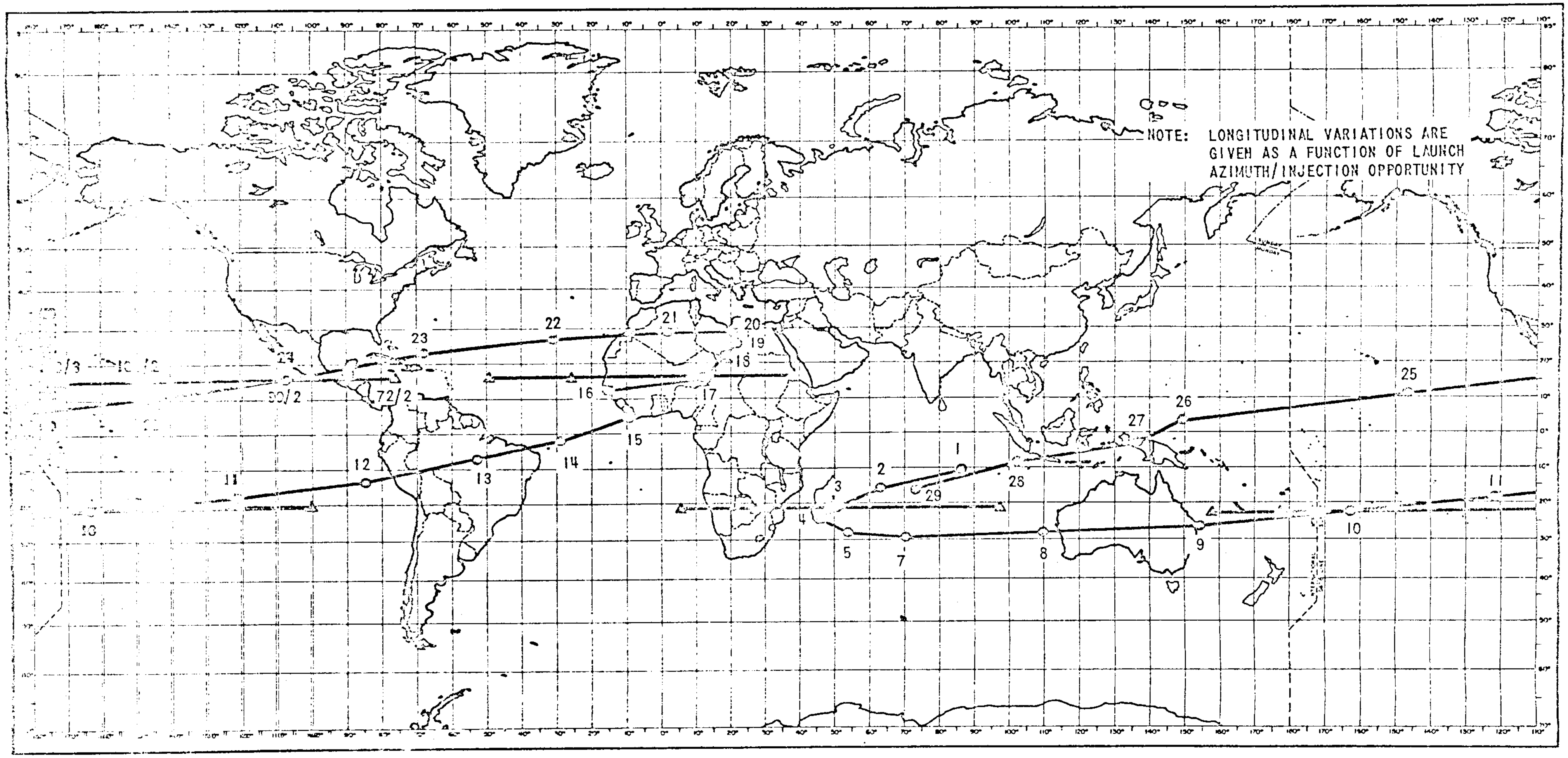

FIGURE 6B: PACIFIC INJECTIONS

FREE RETURN FOCAL POINTS DURING FEBRUARY 1968

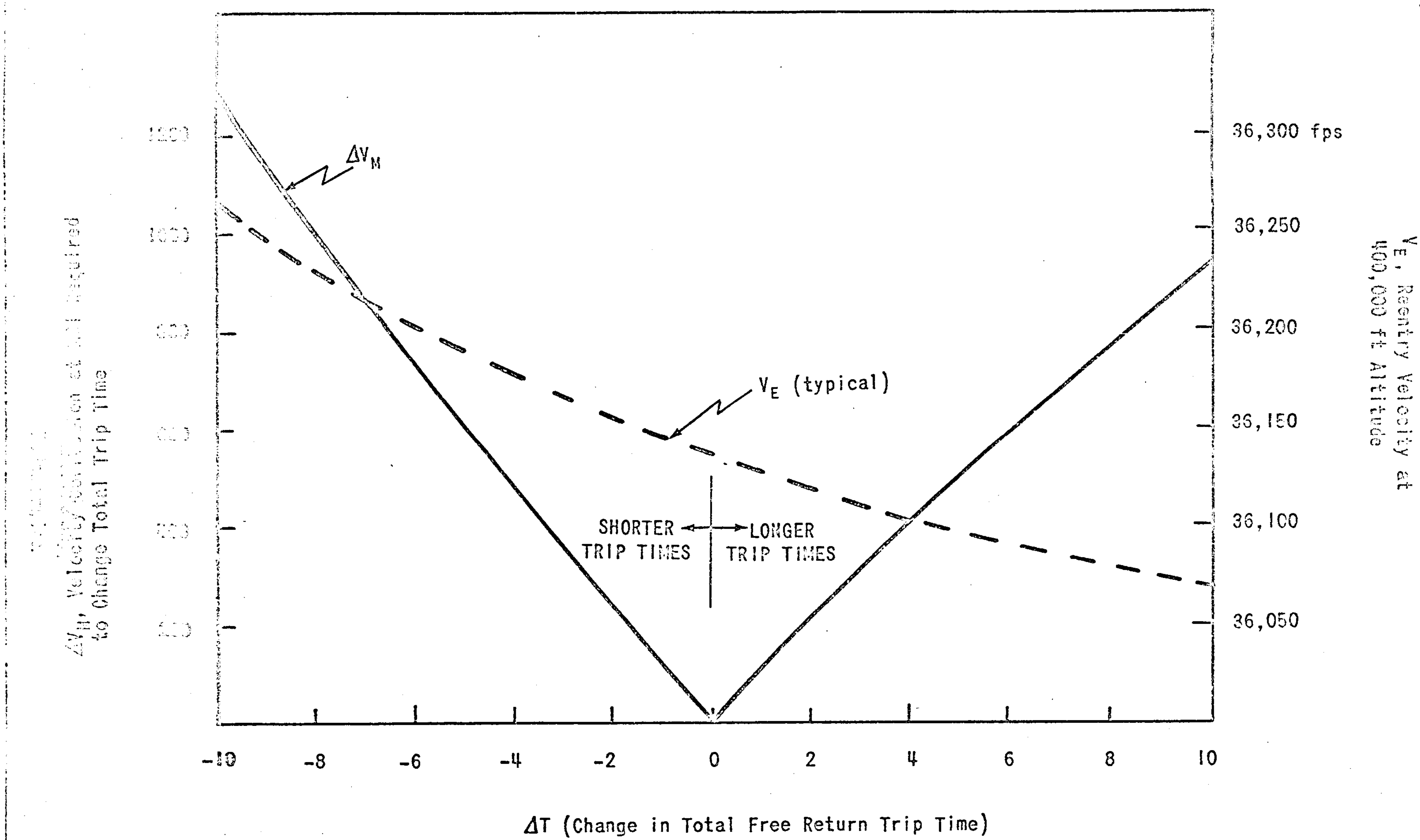

FIGURE 7: REQUIRED ΔV CORRECTION AND TYPICAL REENTRY VELOCITY AS A FUNCTION OF DESIRED CHANGE IN TOTAL FREE RETURN TRIP TIME. THE ΔV CORRECTION IS APPLIED ON THE RETURN LEG AT THE MOON'S SPHERE OF INFLUENCE.

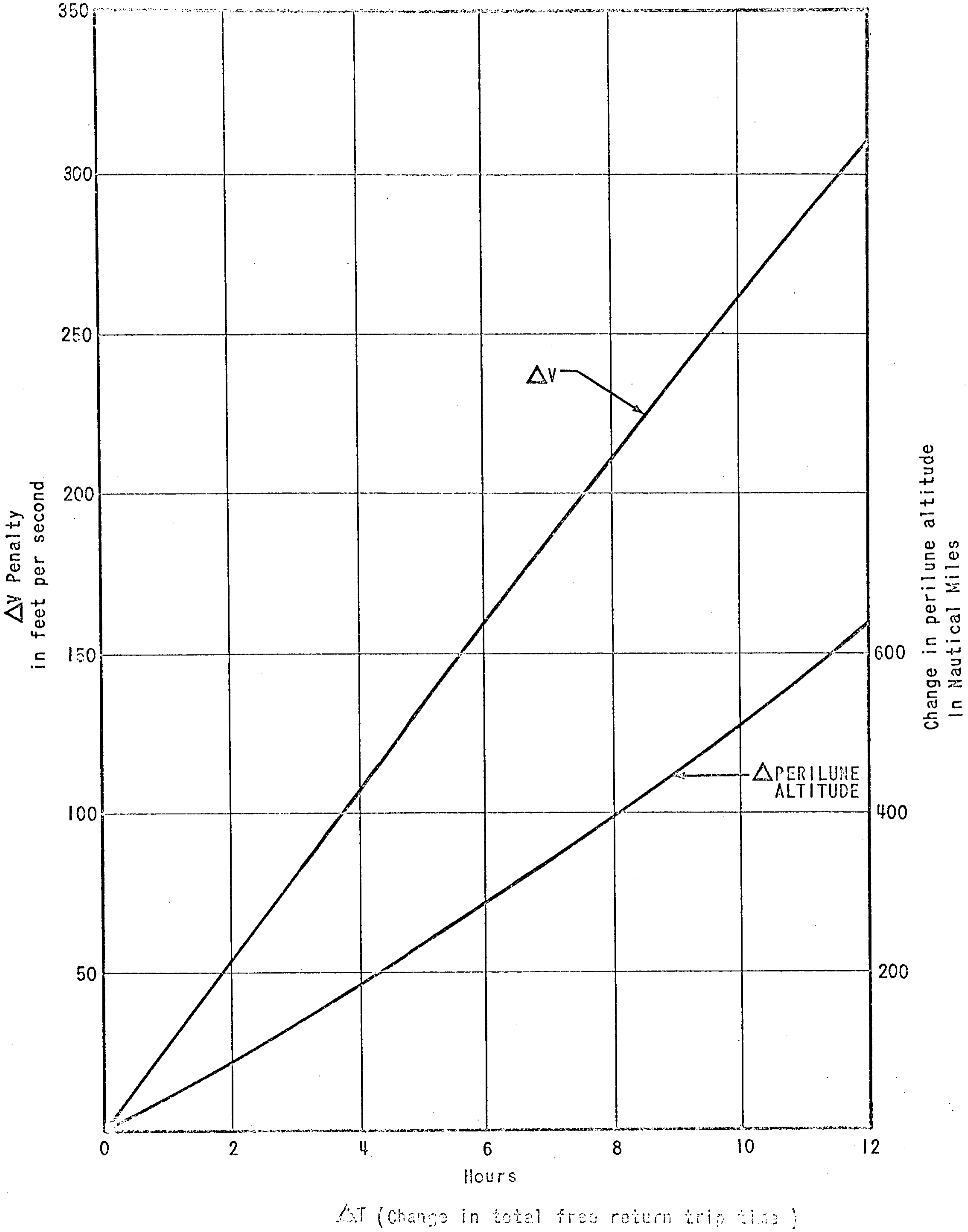

FIGURE 8: REQUIRED ΔV AND REQUIRED CHANGE IN PERILUNE ALTITUDE AS A FU[illegible] OF CHANGE IN TOTAL TRIP TIME [illegible] CORRECTI[illegible] HRS AFTER T[illegible] [illegible]

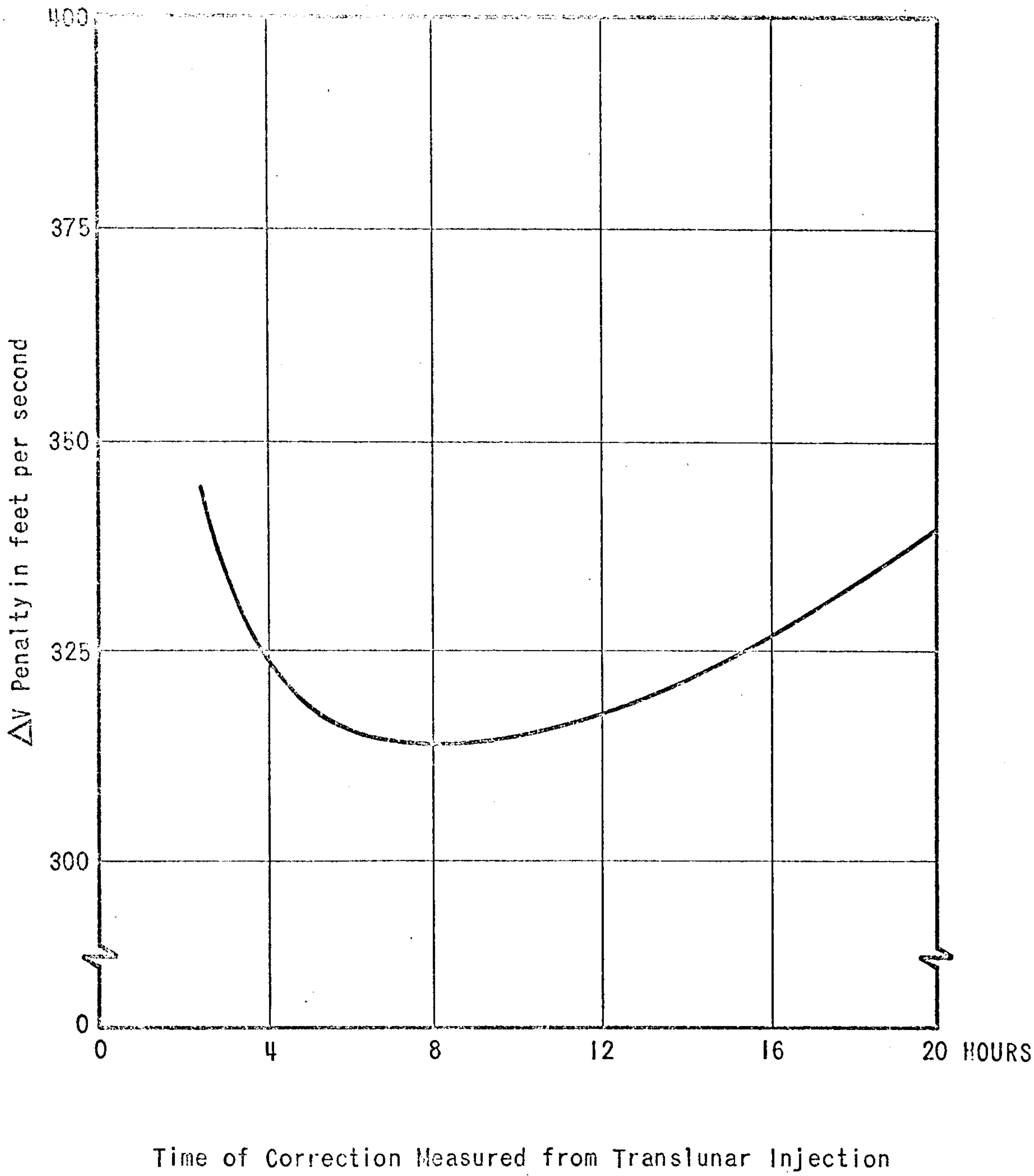

FIGURE 9 - ΔV PENALTY FOR "FREE RETURN SQUARED" PROFILE AS A FUNCTION OF THE TIME OF THE CORRECTION. IN ALL CASES THE CHANGE IN TOTAL FREE RETURN TRIP TIME IS 12.1 HOURS